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Managing food and water security in Small Island States: New evidence from economic modelling of climate stressed groundwater resources

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ABSTRACT

Climate-stressed groundwater resources present a growing challenge for protecting food security and economic sustainability, notably in Small Island Developing States (SIDS). These states are some of the most vulnerable to climate stress because of their large coastlines, vulnerability to rising sea levels, weak access to reliable surface water, and limited food production capacity for handling increased groundwater scarcity. Impacts of climate stressed groundwater resources brought on by irrigation and growing urban demand in SIDS continue to receive widespread attention by both scientists and policymakers. Policies that limit pumping to protect aquifer sustainability reduce short-term economic welfare by unknown amounts that would otherwise be secured by both urban and irrigation water users. Yet, little scholarly research has addressed economic impacts of climate-water stress for the special needs of SIDS for which urban and irrigation pumping compete hydrologically and economically over long time periods. The original contribution of this work is to address that gap by employing downscaled data on precipitation from Representative Concentration Pathways (RCP) climate scenarios. Its novel contribution is to conceptualize, develop, apply, and interpret an integrated hydro-economic framework to understand interconnected physical and economic linkages from managing an unconfined regional aquifer system under each of three climate and two policy scenarios. The application is to Barbados, a SIDS, for which current and future irrigation and urban demands compete for water. The framework integrates groundwater hydrology, climate scenarios, economics, land use, and groundwater management, with the intent to mitigate impacts of climate stress on current economic values of water as well as protecting future aquifer sustainability. Results provide a framework to guide water management for SIDS vulnerable to climate stress for which water of the right quantity, quality, timing, location, and price are essential elements of economic development.

1. Background

Meeting growing water demands for food production and urban use in water scarce communities presents an ongoing and growing challenge, compounded by emerging threats and continued evidence of the high economic costs of climate change (USGCRP, 2018). Climate-stressed groundwater resources present a growing challenge for protecting food security and economic sustainability, notably in Small Island Developing States (SIDS). Reduced water availability induced by climate change could result in undesirable consequences on both economic activities and environmental sustainability. Better understanding the economic impacts of climate change on water use, water availability, water supplier livelihoods, and consumer welfare is needed to facilitate more efficient and sustainable adaptation and mitigation measures to improve water sustainability and allocation among competing water sectors.

This research develops an original modeling framework to investigate measures to integrate economic, policy design, and implementation to address hydrological impact of climate change on groundwater resources in regions facing increased challenges managing its scarce water. Toward this end, a downscaled regional dataset on precipitation from Representative Concentration Pathway (RCP) emission scenarios (RCP2.6, RCP4.5, and RCP8.5) is integrated to formulate an optimization model of groundwater hydrology, economics, and policy application to assess the economic impact of climate change on groundwater sustainability, water supplier and water user income, and consumer economic welfare from abstracted water.

Water demands under several climate scenarios are estimated for several water sectors including agricultural and urban use. The economic impacts of two abstraction strategies are investigated, one for

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protecting long term aquifer sustainability and another for protecting short term water demands and use. While the framework is developed and applied for the Island country of Barbados (Fig. 1), its insights could see application to SIDS generally that face a high dependence on groundwater brought on by weak hydrologic and economic access to reliable surface supplies.

2. Introduction

The size, sign, source, and impacts of climate change continue to receive much debate. All continue to attract growing attention by the press, from the scientific community, and in the policy realm. Although not known with complete certainty, climate change is likely to have considerable impacts on groundwater resources availability by reducing groundwater recharge as well as promoting greater discharge through more pumping to meet current and emerging economic demands. Evidence of climate change impacts on groundwater resources has been found in Central Europe and South America (Dams et al., 2012; Eckhardt and Ulbrich, 2003; Melo and Wendland, 2017), and in many other places. The reduction in aquifer recharge is induced by increased temperature, rising plant evapotranspiration (ET), and decreasing precipitation (Kambale et al., 2017; Shrestha et al., 2016). Several regions internationally could experience significant decreases in aquifer recharge levels and therefore become more vulnerable to climate change (Döll, 2009). The decline of groundwater recharge, could be higher than the decline in precipitation, the main source of recharge (Ali et al., 2012; Ng et al., 2010). As a result, it becomes important to understand the relationship between climate change, pumping stress, and effective groundwater resource availability. However, projecting levels and changes in groundwater recharge and therefore the groundwater availability over many years is a complex task associated with high uncertainty, especially in regions for which most water use activity depend heavily on little else besides groundwater for economic benefit (Arnell and Lloyd-Hughes, 2014; Earman and Dettinger, 2011; Green et al., 2011; Harou et al., 2009).

In regions that lack a reliable surface water source such as rivers and lakes, high sensitivity to climate change is expected where anticipated decreased precipitation will produce lower recharge to the aquifer system (Bailey et al., 2016; Scibek and Allen, 2006). Recent research has highlighted that Karst aquifers in particular (Loaiciga et al., 2000) are among the most vulnerable to climate change, where estimating groundwater recharge poses challenges (Jia et al., 2017; Jones and Banner, 2003; Stevanovic et al., 2015).

A Karst aquifer is a system of high interconnectivity between surface and groundwater, consisting of soluble coral limestone, for which recharge occurs through sinkholes, gullies, caves, and infiltration. Several quantitative approaches have been suggested to estimate the groundwater recharge, discharge, and storage capacity for Karst aquifers (Allocca et al., 2015; Butscher and Huggenberger, 2008; Entezari et al., 2016; Geyer et al., 2008; Hartmann et al., 2014; Kavouri et al., 2017).

The Caribbean Region contains several SIDS with Karst aquifers (Mangini et al., 2007; Sumrall et al., 2013), and could experience high reduction in recharge even under moderate variability in precipitation (Hartmann et al., 2014) making SIDS in this part of the world more vulnerable to the future climate change (Barkey and Bailey, 2017; Holding et al., 2016). In such cases, land use and abstraction management could be an efficient and sustainable approach to enhance aquifer recharge and sustainability (Charlier et al., 2015; Conti and Gupta, 2016). Further growing water scarcity in many small island aquifer systems climate change could increase saltwater intrusion pressure on groundwater and reduce effective storage capacity (Chang et al., 2016; Lathashri and Mahesha, 2016).

Balancing water supply and demand in this environment is a major and largely unaddressed challenge, for which climate change can stress groundwater supply and for which growing urbanization and human activities are likely to escalate water demand. In light of high uncertainty associated with groundwater resource availability (Crosbie et al., 2010), estimating water demand for different human and environmental uses in the face of cost changes that would alter that demand is even more difficult. The uncertainty of demographic and economic factors, as well as climate change uncertainty, presents more challenges for accurate water demand projection that properly adjusts to climate stresses not seen historically. Factors such as population growth, escalating demand for food, and energy production all serve to make the projection of water demand an unresolved challenge to date (Carter and Parker, 2009). Recent findings (Abramson et al., 2014) indicate that water demand from groundwater resources is affected by several factors including population, income, tourism, as well as the price charged to water users (Gohar and Cashman, 2015). In many cases, reallocating limited groundwater among sectors in addition to new technology intervention such as desalination is becoming more important to maintain the acceptable water demand for food and domestic uses (Al-Juaidi et al., 2014).

In conditions where more than one economic sector competes for use of available groundwater, economic instruments and policies that signal the scarcity value of water could help protect the limited groundwater resources (Bann and Wood, 2012; Compernolle et al., 2013; Gohar and Cashman, 2017). Yet, little peer reviewed attention has been devoted to inform difficult economic policy choices (Holman, 2006; Sanchez, 2003).

Economic policies could integrate with groundwater management for more sustainable outcomes. One option that has been found to be productive in reducing water supply shortages while managing aquifer recharge under threats of climate change is to regulate groundwater abstraction (Baruffi et al., 2013). Limiting groundwater abstraction rates, especially if combined with subsidies for subsistence uses such as drinking, could be an efficient and equitable tool to control saltwater intrusion and reduce economic losses of water shortage as well (White et al., 2003). However, success in implementing those types of groundwater adaptations should be evaluated against consequences for their economic performance.

Despite increasing attention directed to the management of groundwater resources and the potential impact of climate change on those resources, little attention has been paid to the impact of climate change on aquifers for the special needs and unique conditions facing all SIDS and the challenges that they face, for which some of those needs have been described earlier (Gohar and Cashman, 2016; Holding et al., 2016). Moreover, the interdependence between economic and physical impacts of climate change on groundwater resource availability tied to stakeholder welfare has not been investigated in much detail by previous peer-reviewed research. Some recent work has assessed impacts of climate change on water resources availability, groundwater storage, land use, and aquifer characteristics as well as economic outcomes (Booker et al., 2012; MacEwan et al., 2017; Macian-Sorribes et al., 2017; Rosenberg et al., 2008; Ward and Pulido-Velazquez, 2012). Another body of research has investigated the economic and policy dimension of climate change, but has conducted these investigations largely in isolation of some important biophysical characteristics (Krishnamurthy, 2017; Roumasset and Wada, 2014).

The paper expands on earlier work (Gohar and Cashman, 2017) for which a hydroeconomic methodology was presented to assess the impact of climate changes and variability on farm livelihoods and food security. In that earlier work, a groundwater hydrological model was integrated to account for distinguishing climate change, climate variability, and double impact of climate change and climate variability. It investigates the separate as well as joint impacts on agricultural production and food security. By contrast, for the current work, the hydroeconomic model presented by the previous research has been integrated and upgraded to three RCP climate emission scenarios (RCP2.6, RCP4.5, and RCP8.5) for the period of 2018 to 2100. Another improvement in the current work is to integrate urban water demand as a dynamic factor, in which demands grow yearly, based on population

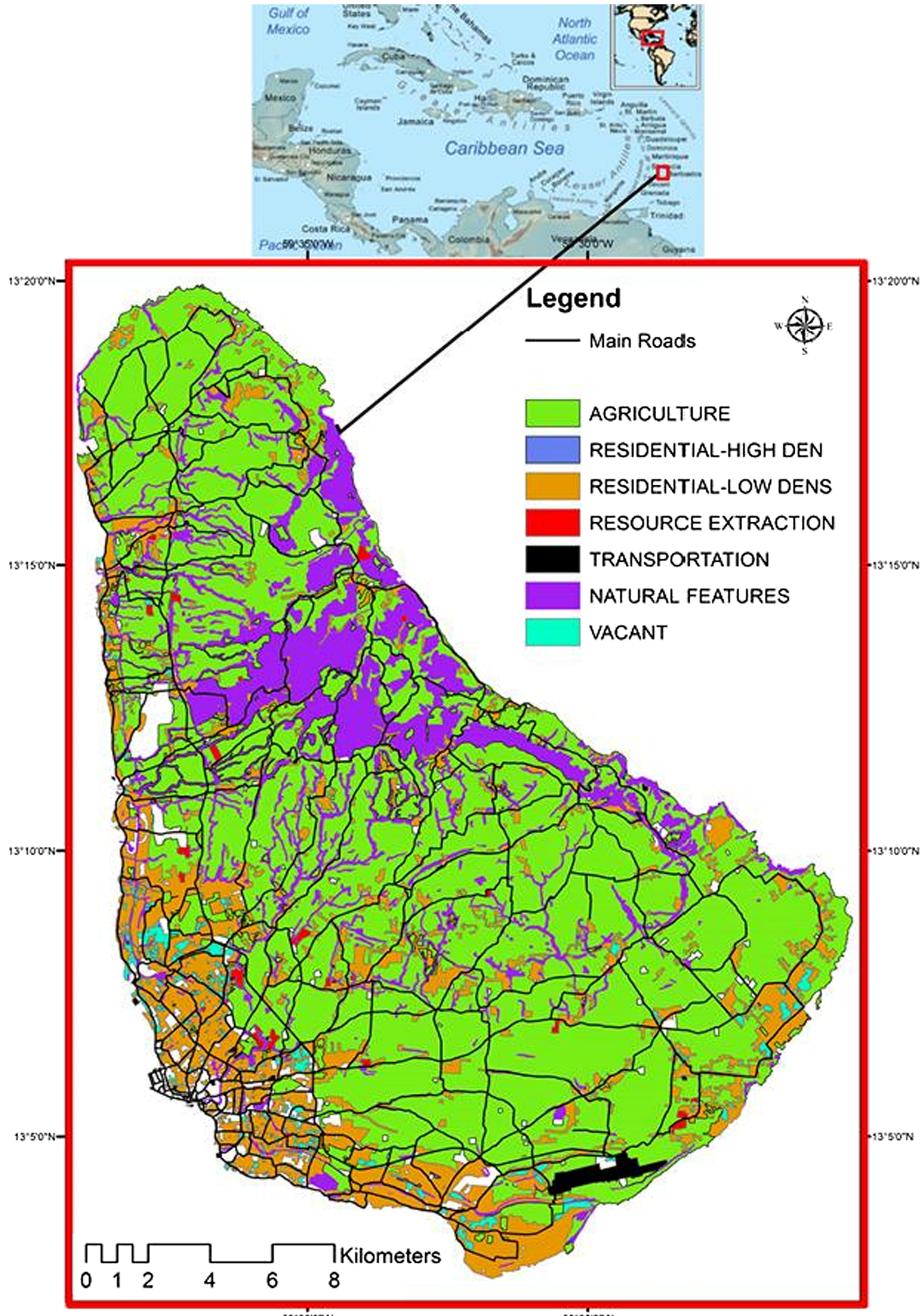

Fig. 1. Barbados land use categories.

growth forecasts (Barbados Economic and Social Report Minister of Finance and Economic Affairs Barbados. Selected Volumes, 2018) rather than treating it as a static stress. Yet another improvement is that the model assesses the impacts of two groundwater abstraction strategies: unconstrained vs. constrained abstraction. Impacts on water user welfare and water supplier revenue are both investigated. To achieve those goals, a total of eight independent scenario combinations were established. While our model was developed and applied for

Barbados, the framework could be applied to SIDS with similar characteristics, which include the Pacific, Caribbean, Africa, Indian Ocean, Mediterranean and South China Sea coalitions of SIDS (United Nations, 2018).

The model formulated for this paper addresses some of those gaps by integrating a variety of hydrologic, agronomic, policy, and economic processes. While it is difficult to integrate all inputs, outputs, policy choices, and economic outcomes with both accuracy and precision, it is more integrated than most previous models, as it accounts for physical, economic, agronomic, and sustainability processes. It also considers characteristics that are important to SIDS communities: often exclusive dependence of groundwater, limited access to short run substitutes for domestic food production such as expanded food imports, and high dependence on heavy fluctuations in precipitation as a contributor to aquifer recharge. This work contributes to filling those gaps by conceptualizing, developing, and applying a modeling framework to address these special conditions of SIDS described above. In particular, our framework makes the following original contributions to the peer reviewed literature:

- An integrated economic framework connects the physical characteristics of the groundwater system to downscaled precipitation climate parameters based on the Representative Concentration Pathway (RCP) emission scenarios.
- It couples characteristics of various economic sectors to the limited groundwater resources while both are influenced by climate water stress.
- It integrates a variety of factors using innovative optimization methods that drive the demand for groundwater for different sectors, particularly irrigated agriculture and urban water use. Accounting for these factors addresses population growth as well as urban demand structural changes.
- It integrates and investigates impacts of two groundwater abstraction policies on groundwater sustainability as well as economic livelihoods for each of these two economic sectors, for various climate change scenarios.
- It simultaneously models impacts of land use changes on food security and agricultural livelihoods together with the impact of climate change and groundwater abstraction policies on groundwater availability and economic welfare.

3. Data and methodology

3.1. Site application

The SIDS of Barbados (Chui and Terry, 2013; Holding et al., 2016; Morgan and Werner, 2014) faces increased pressure on its limited groundwater resources to meet water demands for economic development and food security (Ford and Rawlins, 2007). The island's water security comes almost exclusively from its groundwater resources, for which about 86% of the island aquifer material is composed of Karstified coral limestone. With almost complete access to potable water supplies, water consumption is volumetrically charged, with differentiated pricing schemes for different urban use. Price structure changes alter volumetric use. The country is pursuing policies to improve its domestically produced food security through developing local food production and subsidizing modern irrigation technology such as drip irrigation intended to promote water conservation, to the extent that conversions from traditional to modern irrigation technology actually conserve water (Grafton et al., 2018; Ward and Pulido-Velazquez, 2008b).

In the current work, downscaled data on precipitation secured from several RCP scenarios were integrated with agronomic water demand data (Ministry of Agriculture Food Fisheries and Water Resource Management Planning and Communication Unit, 2018). Those data include information on cultivated area, yield, costs of production, pumping cost, and farm gate prices. Estimated water requirements for crops were secured from FAO publications (Allen et al., 1998; Brouwer and Heibloem, 1986). For the baseline climate condition, average monthly data on precipitation were aggregated to yearly totals. Those data were obtained from selected government agencies in Barbados (Barbados Economic and Social Report Minister of Finance and Economic Affairs Barbados. Selected Volumes, 2018; Barbados Water Authority, 2018). Aquifer characteristics and demographic information such as household size and population were obtained from Barbados Ministry of Finance and Economic Affairs Annual Reports. The latter source was used also to secure the information about land use and land cover. Current water prices were secured from local government data (Barbados Water Authority, 2018).

We downscaled the coarse climate projection to secure a trend at the Barbados airport. To achieve this the IPCC CMIP5 GCM dynamic downscaled data with different spatial resolutions were processed by a bias-corrected pattern scaling method and then re-gridded to a common 720*360 grid (0.5° * 0.5°) using bilinear interpolation. The Model for the Assessment of Greenhouse-gas Induced Climate Change (Wigley, 2008) projections was used to produce 0.0083 by 0.0083° (about 1 km × 1 km) grid maps on a monthly timescale (Meinshausen et al., 2011a,b). This work involved taking the pattern scaling of various Global Climate Models (GCMs) using SCENGEN 5.3 (Wigley, 2008) as well as using a linked-model approach to superimpose the coarser resolution time-dependent GCM projections over a fine spatial resolution Barbados historical baseline dataset to produce localized future climate projections. Climate projections for the Barbados airport meteorological station site, which has the longest continuously assembled historical dataset in the region, were then extracted and reproduced as typical of future trends in Barbados for the base climate scenario (Gohar and Cashman, 2017). That is, we used the trend from the airport to reflect climate scenarios for the whole island. Spatially explicit gridded climate projection maps for Barbados were then visualized using the SimCLIM data management tool (CLIMsystems Ltd., 2013).

3.2. Modeling approach

3.2.1. Overview

This analysis develops, applies, and interprets an optimization model guided by an economic objective. It is an example of a discrete optimal control model with numerous hydrologic, climate, and institutional constraints (Jager and Smith, 2008; Ribeiro et al., 2012; Roseta-Palma and Xepapadeas, 2004). The water resources literature has seen numerous examples of optimal control applications to complex water resources management problems (Gisser and Sanchez, 1980; Grafton et al., 2018; Mulligan et al., 2014; Takeuchi and Moreau, 1974; Ward, 1987).

The objective function to be maximized seeks to achieve the goal of discovering the water development and use pattern that maximizes the discounted net present value of total economic welfare from allocating available groundwater for agricultural and urban use, by climate change scenario and groundwater abstraction policy. That objective is to maximize total economic benefits from groundwater use over years and uses in the face of alternative policies and alternative climate futures.

We selected a base and three RCP climate scenarios; RCP 2.6, RCP 4.5, and RCP 8.5. The model was developed in such way that larger number of climate scenarios and assumptions could be easily incorporated and investigated for future work, so the current model has considerable up scalability not currently in use. The choice of three RCP's represents the aspirational RCP2.6 scenario, for which SIDS in particular have been active in lobbying. The RCP4.5 and 8.5 represent pathways above and below the Business as Usual RCP6.0. They thus represent a spread of potential outcomes which can be used to inform policy. The framework was developed using the General Algebraic Modeling System (GAMS) software (Pazouki et al., 2014). A complete

mathematical documentation is attached in this work as an appendix, for which the GAMS code is available from the authors as well as being posted and available for public use at figshare.com. The following section describes major components and innovations of the model.

3.2.2. Climate change scenarios

Three RCP emission scenarios were integrated to augment the base scenarios; a non-climate stress scenario was used as a baseline for comparison. The base condition scenario assumes no climate stress taking place, for which the study region is assigned the long run average precipitation, 1450 mm/year. The climate scenario RCP 2.6 (van Vuuren et al., 2011) assumes that a global annual GHG emission (measured in CO2-equivalents) reaches its highest level between the years 2010–2020, with emissions declining considerably after those years. Climate scenario RCP 4.5 consists of a moderate climate projection, where the CO2 emissions are expected to increase until 2040, and then decrease subsequently. In contrast, the RCP 8.5 (Riahi et al., 2011) scenario is a high emissions projection that assumes uncontrolled CO2 and methane emissions from human activities with minimal adaptation strategies implementation established by 2100. No other source of affordable water was assumed to be available for current or future use.

3.2.3. Groundwater hydrology

In the case of a single large regional scale aquifer system without rivers, for which water demands are groundwater supplied, precipitation is partitioned among direct plant ET, water runoff, evaporation, and infiltration to the aquifer system. Infiltrated water that feeds the aquifer as recharge is partitioned, including effects of precipitation as well as direct ET lost to aquifer seepage.

In the case of an unconfined Karst regional aquifer system, estimation of the groundwater storage presents a challenge, where recharge can change rapidly due to sensitivity to climatic parameters (Jones and Banner, 2003). Our model simplifies the process of aquifer storage between any two sequential time periods be a function of the storage volume from previous time and infiltration to the aquifer and total groundwater abstraction. Aquifer storage volume is dependent on aquifer storativity as well as plan view surface area. Giving the scarcity of data, we used storativity used by the water authority (Barbados Water Authority, 2018), 0.3, a typical value for Karst aquifers (Gohar and Cashman, 2016).

3.2.4. Economics: Agriculture

Groundwater use for crop irrigation is used to supplement the deficit in meeting crop water demands in dry seasons, achieved through drip irrigation (Gohar and Cashman, 2016). Farmers are assumed to use drip irrigation only when rainfall is less than the maximum ET required to maintain the maximum crop yields and for which drip irrigation can be an economically sound investment (Karam et al., 2014). However, adopting drip irrigation incurs conversion costs that include system installation, energy use, and a water charge. The amount of water used in drip irrigation depends on crop yield as well as climate condition. We adopted a quadratic functional relationship between the yield (dependent variable) and the uptake of soil water derived from precipitation, an independent variable (Liu et al., 2002).

For application of this quadratic model, crop yield increases at a decreasing rate. Applying additional water increases plant biomass and therefore higher yields can be achieved to a point. At the maximum ET stage, no gain in yield is achieved, beyond which at higher applications if carried out decrease yield (Fay et al., 2003; Garbrecht et al., 2004; Orgaz et al., 1992; Pandey and Ramasastri, 2001). Over the economically relevant range, the quadratic functional form was found to be representative for crops such as sugarcane, cotton, wheat, and barley (Grimes et al., 1969; Gulati and Murty, 1979; Liu et al., 2002 ; Zhang et al., 1999).

Following the above discussion, crop yield ($Yield_{akcst}$) was modeled as a quadratic function of ET (ET_{akcst}), where indices (sets), variables, equations, and data sources are defined in the mathematical documentation appendix. A few of the most important ones are briefly summarized here. The equation's intercept (δ_0) and slope (δ_1) are parameters calculated by solving two equations that represent the total observed yield (TY_{jk}) and marginal yield (MY_{jk}) by land use (j) and irrigation technology (k). The term is the change in observed water by land use and irrigation technology. The relations are summarized as:

$$Yield_{akcst} = \delta_{0ak} * ET_{akcst} + \delta_{1ak} * (ET_{akcst})^2 \tag{1}$$

$$TY_{jk} = \delta_{0jk} * ET'_{jk} + \delta_1 * (ET'_{jk})^2 \tag{2}$$

$$MY_{jk} = \delta_0 + 2 * \delta_{1jk} * (ET'_{jk}) \tag{3}$$

Solving the above equations for two unknowns (δ_0) and (δ_1) produces the following calculations for the two desired parameters, which are all based on observed data in (1) – (3).

$$\delta_{0jk} = MY_{jk} - 2\delta_{1jk}(ET'_{jk}) \tag{3a}$$

$$\delta_{1jk} = \frac{MY_{jk} - TY_{jk}}{(ET'_{jk})^2} \tag{3b}$$

Equation (4) below calculates total costs of production, TC, for each crop as the sum of non-water cost of production NWC, and the cost of installing and operating a drip irrigation system, CC, as well as pumping cost, EC, and the cost of purchased water at given water price, PC:

$$TC_{jkcpt} = NWC_{jkcpt} + CC_{jdcpt} + EC_{jdcpt} + PC_{jdcpt} \tag{4}$$

The capital cost of installing drip system, CC per hectare, depends on the capital cost of purchasing the system CCS, the interest rate, r, the system's life span, SL, and the size of any one of many potential subsidies, $Subsidy$, held constant for this analysis, but which we plan to vary for future work. The relationship is expressed as:

$$CC_{jd} = \left\{ \frac{CCS * r}{1 - \left[\frac{1}{(1+r)^{SL}}\right]} \right\} * (1 - Subsidy) \tag{5}$$

Equation (5) shows that farmers who apply drip irrigation technology reduce their financial cost with a government subsidy program that pays for a set subsidy of the purchase cost of the system with a typical life span of SL years' time. For a given subsidy level, the total subsidy payment by the taxpayers who finance the program depends on the total land under drip irrigation.

Those payments are calculated at the discount rate, set to 10%, reflecting the capital scarcity levels often seen in SIDS or other developing countries (Demirgüç-Kunt and Huizinga, 1999). In addition, drip irrigation requires several kinds of operations costs, including the costs of pumps, repair, and replacement. Increasing pumping depth increases the pumping cost per cubic meter, for a given level of water pumping plant efficiency. The cost of pumping, EC (not electrical conductivity), at any time is a function of Kw, the number of KWh needed to lift a unit of water per additional 1 m depth, pumping lift, Kw. It is also affected by the price of energy, Ep, pumping efficiency, E, and the amount of groundwater required to deliver the crop evapotranspiration at maximum yield level ET, as shown below:

$$EC_{jdcpt} = \left[\frac{Kw * Lf_{cpt} * Ep_t}{E}\right] * ET_{jdcpt} \tag{6}$$

The economic performance of irrigated agricultural policy interventions plays a big part of our analysis. Discounted total net farm income by climate scenario and abstraction policy is accounted for by summing net the farm income over crops, irrigation technology, and time. The discounted net present value at discount rate r, of total net farm benefits, by climate scenario and abstraction policy is given by:

$$DTNAB_{cpt} = \sum_j \sum_k \frac{(P_{jcpt} * Y_{jkcpt} - TC_{jkcpt}) * L_{jkcpt}}{(1 + r)^t} \quad (7)$$

where P refers to the farm gate price, Y, crop yield, and L, cultivated land. The consumer surplus, accruing to the crop/food buyer, unknown in advance of the optimization exercise, is used to measure the economic gain or loss to that buyer's measured economic welfare from a crop price change brought on by a policy adjustment or climate change stress. Discounted consumer surplus is shown below in (8). For the special case of the linear model we used, it is calculated as half the difference between the maximum (reservation) price β_0 and the actual model-optimized (endogenous) price multiplied by the total production supplied from a specific crop TP summed over irrigation technologies k in use. The discounted consumer surplus is independent of the mix of irrigation technologies used to supply crop production, as it depends only on a crop's total production (Gohar et al., 2013).

$$DACS_{jcpt} = \frac{0.5 * [(\beta_{0j} - P_{jcpt}) * \sum_k TP_{jkcpt}}{(1 + r)^t}$$

3.2.5. Economics: Urban water demand

For urban water demand, we identify a demand function, for which a linear approximation described below. Employing external information (from the literature, as described in the math appendix) on water demand elasticity, the (inverse) demand function is expressed as:

$$Pu_{ucpt} = \alpha_{0_u} - \alpha_{1_u} * (TD_{ucpt}) \quad (9)$$

The term Pu is the urban water tariff by urban subsector u, while TD is total water demand by sector. The terms $\alpha 0$ and $\alpha 1$ are the intercept and the slope for the inverse demand function respectively, which are calculated based on observed price and use as well as estimated price elasticity of demand. For future years, total water demand by sector is the individual demand multiplied by the sector's population or use, which grows from a known starting population level.

Total discounted consumer surplus can be calculated from the demand function (9), based on the area under the demand function exceeding the price of urban water as:

$$DUCS_{ucpt} = \frac{0.5\,[(\alpha_{0_u} - Pu_{ucpt}) * TD_{ucpt}]}{(1 + r)^t} \quad (10)$$

The urban supplier bears costs for providing water to the urban buyers, and for this analysis is required to have total revenues at least as high as total costs (producer surplus equal to or greater than zero). Total discounted urban net benefits, $DTNUB$, by water suppliers can be calculated below from (9), whereas $ATUC$ is the total average cost of supplying urban water by climate scenario, abstraction policy, and time period. The supply cost is function of the operation and maintenance costs (O&M) that vary by the pumping depth of groundwater, for which more energy cost is required for deeper pumping. The term NL is the distribution network water's losses, including leaks and non-revenue water (Marin, 2009). It is set to a percentage of total water supplies for the whole system, measured in volume of water deliveries per year.

$$DTUNB_{cpt} = \sum_u \frac{(Pu_{ucpt} - ATUC_{cpt}) * (TD_{ucpt} + NL_{pt})}{(1 + r)^t} \quad (11)$$

The objective function to be maximized uses the terms in Equations (7), (8), (10), and (11). It sums discounted net present value of urban and agricultural water uses over the model's time horizon, when the water is pumped from the regional aquifer. The objective is to:

$$Maximize\ TSEW_{CP} = \sum_u \sum_t DTANB_{cp} + DACS_{cpt} + DTUNB_{cpt} + DUCS_{ucpt} \quad (12)$$

Our investigation seeks a water use program that maximizes the total economic welfare over sector and time period, defined as the sum of consumer and producer surplus over all water uses shown in (12). The benefit of formulating this approach to discovery of economic efficiency in water use is an accounting of the most important economic processes that influence the economic value of the two water-using sectors we investigated, urban and agricultural. The dynamic interaction between the suppliers and consumers of domestic water and crops are tracked in all periods.

For example, farms secure a higher income from higher food prices, other things equal. Higher food prices encourage farmers to expand the scale of crop production by driving up the marginal cost of supply. However, the economically efficient crop price depends also on the consumer affordability of those prices (demand), where food buyers see increased consumer surplus that occurs with lower crop prices passed onto final food buyers. Resolving the welfare conflicts between food and water suppliers and users by maximizing discounted net present value summed over uses and time periods is a method that has been used in some recent works (Bozorg-Haddad and Marino, 2011; Broad et al., 2010; Brouwer et al., 2004; Noory et al., 2012; Pulido-Velazquez et al., 2013; Pulido-Velazquez et al., 2006; Ward and Pulido-Velazquez, 2008a).

The welfare-maximized outcome from (12) is established at the point where the sum of consumer and producer welfare from water development and management is made as high as possible while consistent with available water constraints and climate data used. Details are in the mathematical appendix.

3.2.6. Policy analysis

In this work, climate change, groundwater hydrology, and economics are integrated to discover a path forward to sustainable groundwater management and policy. Similar aspirations have motivated the development of many hydroeconomic models in recent years (Booker et al., 2012; Goor et al., 2011; Harou et al., 2010; Huffaker and Whittlesey, 2000; Maneta et al., 2009; Ward and Pulido-Velazquez, 2008a). The overarching goal of an economically efficient (optimized) water policy is to ensure that water can be provided to users in the quantity, quality, timing, and location to meet their needs at an affordable price.

Faced with a situation for which the capacity to economically satisfy demand from existing sources becomes unsustainable, there are two approaches to formulate policy. The first is to make no special plans to address groundwater mining. The second policy investigates the potential for more sustainable use of existing resources. Each is discussed in detail.

First Policy: We addressed the first option through the "Unrestricted Abstraction" policy. For that policy urban water demands are satisfied by allowing a level of abstraction that meets consumer demands with no regulation imposed on pumping. This can only be achieved as long as water remains in an aquifer and that water can be abstracted affordably at a rate that meets demands. In the face of little recharge compared to pumping demands, there are practical limits to this course of action, as no aquifer has infinite storage capacity to sustain condition when pumping exceeds recharge (Pierce et al., 2013). For our SIDS, subsidized potable water is provided at lower prices than its average production cost, especially for household uses. This course of action implies there are few affordable economic incentives to reduce demand. Under these conditions, the utility supplier continues to run a financial deficit, subsidized by the taxpayers, which is the case for may water authorities around the world (Ward and Pulido-Velazquez, 2008a; Ward and Pulido-Velazquez, 2009; Yates et al., 2013).

Second Policy: This policy approach considers the potential for more effective use of existing resources. Two routes for achieving this are increasing supply or decreasing demand. Increasing supply in this case can be taken to mean using the available water resources more effectively to ensure that more of what is available reaches consumers through measures such as non-revenue detection as well as leak detection and repair. In other words, measures are implemented to ensure

that the real costs from the water distribution system are reduced when larger than the reduced benefits. There is a tradeoff between the cost effectiveness of reducing losses compared to other measures (e.g. reducing demand), sometimes referred to as the economic cost of leakage control. This paper investigates the effect of constraining abstraction through regulation as a mechanism to limit demand, which is implemented while also protecting a terminal period level of aquifer storage. This option is titled “constrained groundwater abstraction.” In this scenario, a minimum terminal storage volume in the aquifer is set as a mechanism to protect sustainability.

Alternatively, economic instruments such as water pricing can be used as a measure to curtail low-valued uses on those uses for which customers are responsive to price signals, with important application to low valued uses such as outdoor landscaping and forage crops. It could also have a positive effect on the financial position of the water utility with lower consumption being more than financially offset by higher prices, in light of a low price elasticity of demand for urban use.

4. Results and discussion

4.1. Aquifer use and sustainability

Fig. 2 presents findings of our model for annual aquifer storage by groundwater abstraction policy, climate scenario, and year, in million cubic meters per year. It shows that groundwater sustainability, by which the aquifer’s terminal status is protected to a level at least as high as its 2018 starting value, cannot be achieved in the face of any of the climate scenarios without an aquifer protection intervention to guard against unsustainable pumping. With no constraints on groundwater abstraction, the country’s groundwater faces effective hydrologic as well as economic depletion as seen in the figure. For a SIDS like Barbados, the capacity to meet water demand for food production as well as urban water use while also protecting aquifer storage for future use represents a dilemma for which there are few affordable solutions. In the absence of abstraction constraints, the figure shows little difference among impacts on the aquifer across the various climate scenarios. Abstraction restrictions have a more pronounced effect on aquifer storage over time than the climate scenario selected. Under all circumstances, the country faces groundwater depletion by the year 2100 if it meets growing demands for urban use and irrigated agriculture without pumping limitation policy, since pumping would exceed recharge by so much for so long.

Fig. 3 shows groundwater abstraction summed over uses, by groundwater abstraction policy, climate scenario, and year, in million cubic meters per year. The figure shows economically optimized levels of groundwater abstraction that would take place without and with groundwater abstraction limits. Economically optimized refers to the water use pattern that maximizes discounted net present value of total economic welfare, described in Eq. (12) earlier, summed over uses and years.

Without pumping constraints, the figure’s solid lines show that economically optimized groundwater abstraction reaches the limit of about 75 MCM under the base climate scenario, while it ranges between 66, 65, and 63 MCM for the RCP 2.6, RCP 4.5, and RCP 8.5 climate stressed scenarios respectively. As the island receives less recharge to its aquifer under greater climate stress, less is available for longer term aquifer protection as for satisfying current levels of urban and food demand.

Under a constrained abstraction policy to protect the aquifer, the dashed abstraction lines show that while long run aquifer sustainability can be protected, groundwater use declines over time in the face of an increasingly stressed climate condition, although use reductions are nearly eliminated after the year 2070 for all climate stress scenarios. Implementing the constrained pumping policy reduces the total annual average groundwater abstraction to an average of about 40, 33, 31, and 29 MCM per year for base, RCP 2.6, RCP 4.5, and RCP 8.5 scenarios respectively. As anticipated, pumping reductions are large in the face of increased climate stress scenarios, all of which must occur to achieve long run aquifer protection with reduced aquifer recharge.

Fig. 4 shows the average cost of groundwater abstraction for urban use, by groundwater abstraction policy, climate scenario, and year, in $US per cubic meter. The figure shows an increase in average terminal year price from $0.129 to $0.155 per cubic meter, when pumping is constrained compared to an unconstrained pumping scenario. Similar costs are shown for all climate scenarios. By far the largest burden of that pumping restriction is borne by irrigated agriculture, shown more

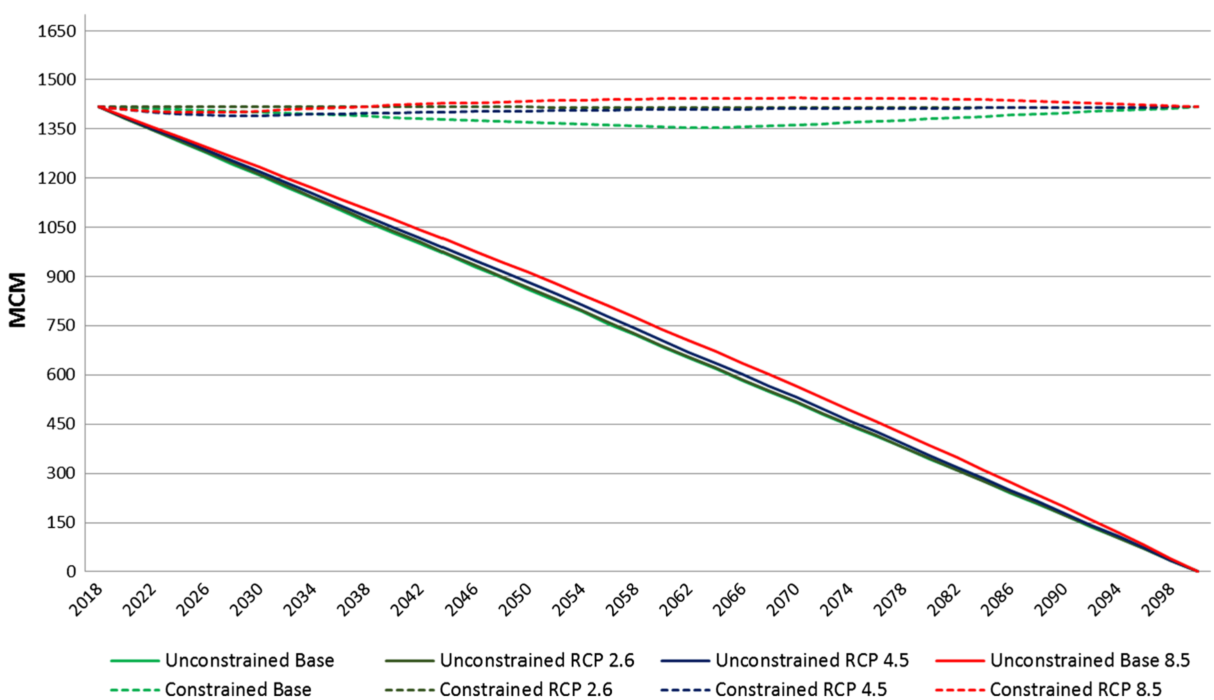

Fig. 2. Annual AquiferStorage by Groundwater Abstraction Policy, Climate Scenario, and Year, Barbados, Million Cubic Meters.

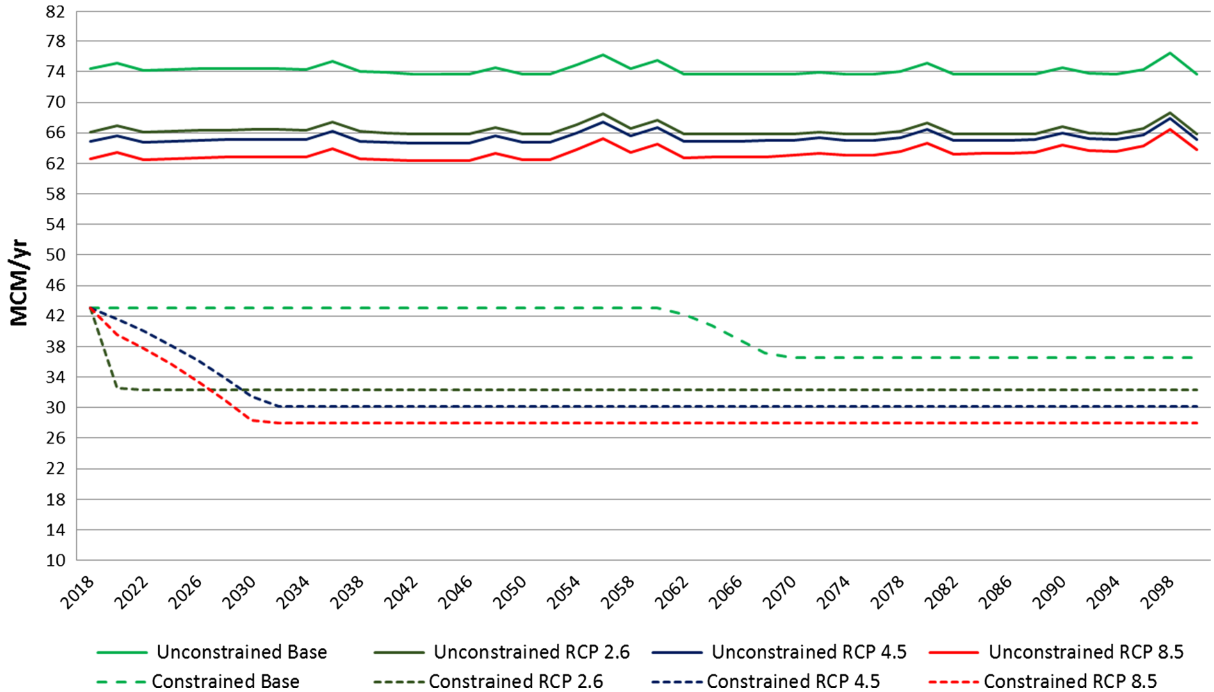

Fig. 3. Groundwater Abstraction for Urban and Irrigation, by Groundwater Abstraction Policy, Climate Scenario, and Year, Million Cubic Meters/year, Barbados.

clearly in Table 1 as discussed below. The price of elasticity of demand for urban use is comparatively small in Barbados as is the case in many urban water utilities worldwide (Kreins et al., 2015; Worthington and Hoffman, 2008).

4.2. Groundwater use by sector

Table 1 shows annual optimized water demands by sector, abstraction policy, and climate scenario in million cubic meters per year, from 2018 to 2100. With abstraction limits, optimized agricultural water use will decline markedly compared to without those limits, ranging from use levels the range of about six to nine percent of unconstrained levels, depending on the climate water stress scenario.

The heavier adjustment burden from pumping restrictions is shouldered by crop irrigation. Urban use, as stated above, a has low price elasticity of demand, averaging about −0.42 for our Barbados utility (Barbados Water Authority, 2018). This low elasticity occurs because urban users in Barbados have limited opportunities for substitution in the face of increased prices, resulting in minimal decline in their average consumption in the face of growing pumping depth and associated increased utility pump costs. Our results reflect well-established findings that have been replicated many times over many investigations where irrigated agriculture competes with urban use in the face of reduced supplies (Merrett, 2003; Rosenzweig et al., 2004). When this competition occurs, urban water use is effectively prioritized in the face of its low price elasticity of demand, with less water allocated to irrigation uses, partly because of impacts on raising crop production costs and elevating pressure on food imports in places where adequate food importing payment capacity is available.

One important factor is that the population growth for Barbados is

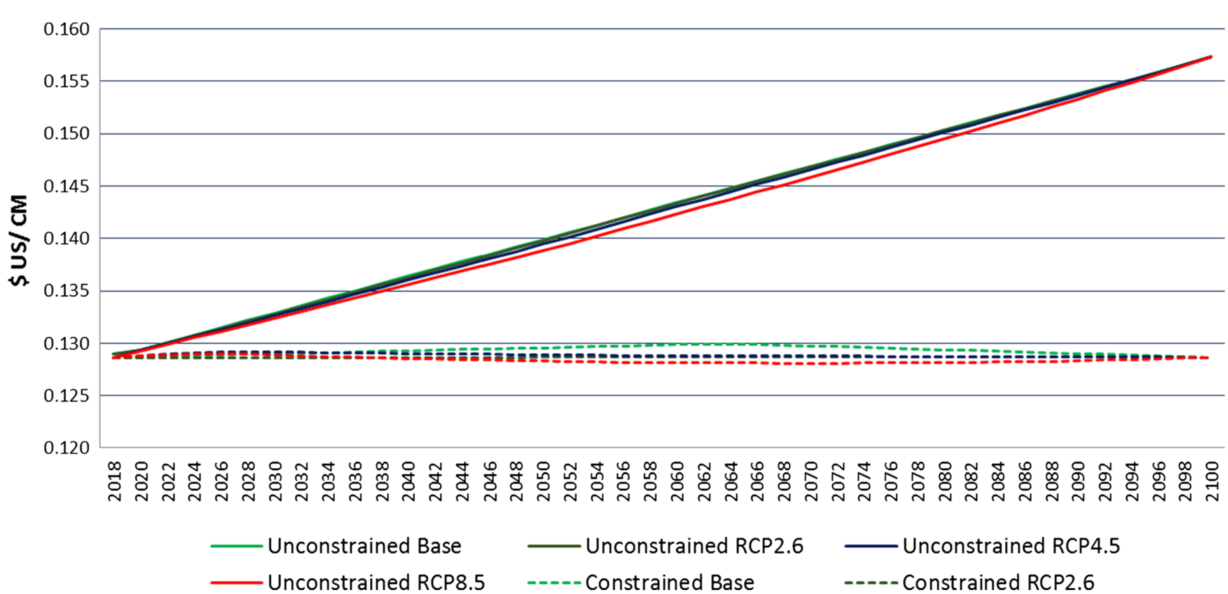

Fig. 4. Average Cost of Groundwater Abstraction for Urban Use, by Groundwater Abstraction Policy, Climate Scenario, and Year, Barbados, $US / MCM.

Table 1
Annual Water Demand by Sector, Abstraction Policy, and Climate Scenario in Million Cubic Meter/Year (2018–2100).

Year	Unconstrained Groundwater Abstraction								Constrained Groundwater Abstraction							
	Agricultural sector				Urban scetor				Agricultural sector				Urban sector			
	base	RCP2.6	RCP4.5	RCP8.5	base	RCP2.6	RCP4.5	RCP8.5	base	RCP2.6	RCP4.5	RCP8.5	base	RCP2.6	RCP4.5	RCP8.5
2018	15	7.1	5.9	3.6	42	42	42	42	1.4	1.3	1.2	0.9	30	30	30	30
2022	15	7.2	5.9	3.7	42	42	42	42	1.4	1.3	1.2	0.9	30	22	28	26
2026	15	7.3	6.0	3.7	42	42	42	42	1.4	1.3	1.2	1.0	30	22	25	23
2030	15	7.4	6.1	3.8	42	42	42	42	1.4	1.4	1.2	1.0	30	22	22	20
2034	15	7.4	6.1	3.8	42	42	42	42	1.4	1.4	1.3	1.0	30	22	21	19
2038	15	7.5	6.2	3.9	42	42	42	42	1.4	1.4	1.3	1.0	30	22	21	19
2042	15	7.5	6.3	4.0	42	42	42	42	1.4	1.4	1.3	1.0	30	22	21	19
2046	15	7.5	6.4	4.1	42	42	42	42	1.4	1.4	1.3	1.0	30	22	21	19
2050	15	7.6	6.4	4.2	42	42	42	42	1.4	1.4	1.3	1.1	30	22	21	19
2054	15	7.6	6.5	4.3	43	43	43	43	1.4	1.4	1.3	1.1	30	22	21	19
2058	15	7.5	6.6	4.3	42	42	42	42	1.4	1.4	1.3	1.1	30	22	21	19
2062	15	7.5	6.6	4.4	42	42	42	42	1.4	1.4	1.3	1.1	29	22	21	19
2066	15	7.5	6.6	4.5	42	42	42	42	1.4	1.4	1.4	1.2	27	22	21	19
2070	15	7.5	6.6	4.6	42	42	42	42	1.4	1.4	1.4	1.2	25	22	21	19
2074	15	7.5	6.7	4.7	42	42	42	42	1.4	1.4	1.4	1.2	25	22	21	19
2078	15	7.5	6.7	4.8	42	42	42	42	1.4	1.4	1.4	1.2	25	22	21	19
2082	15	7.6	6.7	4.9	42	42	42	42	1.4	1.4	1.4	1.3	25	22	21	19
2086	15	7.6	6.7	5.0	42	42	42	42	1.4	1.4	1.4	1.3	25	22	21	19
2090	15	7.6	6.8	5.2	42	42	42	42	1.4	1.4	1.4	1.3	25	22	21	19
2094	15	7.6	6.8	5.3	42	42	42	42	1.4	1.4	1.4	1.3	25	22	21	19
2098	15	7.6	6.8	5.4	44	44	44	44	1.4	1.4	1.4	1.4	25	22	21	19
2100	15	7.6	6.8	5.5	42	42	42	42	1.4	1.4	1.4	1.4	25	22	21	19

expected to decline after midcentury, based on projections of United Nations, giving rise to more water available for irrigation uses. The greatest intensity of climate impacts on precipitation will take place after mid-century. Thereafter, more reliance on groundwater for abstracting is expected in the long run to meet crop water requirements or deficits caused by declining precipitation. Without abstraction limits, urban water use will consume higher amounts of water, where annual groundwater abstraction shows comparative stability at about just over 40 MCM per year for all climate scenarios.

Under these described constraints on the groundwater abstraction, less water will be allocated to irrigation uses and more economic benefits can be secured through urban water use. While it will be hard to sustain existing observed per capita urban water consumption levels, optimized urban uses shown in Table 1 will maintain between about 60 percent and 71 percent of unconstrained urban use in the face of pumping restrictions under the base climate scenario and from 71 percent to about 50 percent under the greater climate stress.

4.3. Crop prices and food security

Many SIDS are vulnerable to climate change in addition to facing high dependence on groundwater to protect and sustain food production. For these communities, it remains a central scientific and policy issue to investigate how climate change could affect both food prices and farm income for SIDS in the years ahead. Table 2 presents average farm gate crop prices by abstraction policy and climate scenario, in $US 1000 per ton. Model results are based on the assumption of no additional capacity to pay for food imports when domestic food production is stressed with reduced output of pumping for agriculture. To the extent this assumption is violated, results of food price increases shown in Table 2 are overstated. The table shows that food security, proxied by increased prices, will be negatively impacted by climate stress as well as by constrained groundwater abstraction. Effects on elevated crop prices from either climate stress or aquifer pumping limits vary by crop. Some crop prices actually fall slightly with a more severe climate stress under pumping restrictions, e.g., cabbage, cucumber, and onions, because not all crop price elasticities are equal. So not all production responds proportionally to increased pumping depth.

Data on price elasticities of demand, the percentage change in food demand from a one percent change in price, were adapted from a 2016 published work (Walters and Jones, 2016). Those elasticities were found to range from -0.179 to -0.800 for the crops described in table 2 (individual elasticities not shown). Imports and exports are included in those elasticities, so some of the changes in consumer surplus from supply changes accrue to food consumers outside our study area of Barbados.

Consumers face higher food prices under a more severely climate stressed water supply scenario, absent offsetting food imports. Reduced precipitation induced by climate change will reduce yields from rainfed crops and therefore less food will be shipped to markets, increasing food prices, most noticeable in areas supplied by local food production. In addition, sustaining urban water consumption under the more several climate-stressed water supplies will pull water from irrigated agriculture to other sectors to the extent that the potential for formal or informal markets exist. With less water available for irrigation with increased climate pressure, Table 2 shows higher optimized food prices, since food prices increase with reduced food production, brought on by greater climate stress or by constrained groundwater abstraction. Average annual increased food prices range between about 35% and 150% growth as a result of a change from the base to the most pessimistic climate scenario.

Constraining groundwater abstraction sufficiently to protect and sustain long term aquifer levels adds more pressure to the capacity to sustain shorter term food security absent offsetting food imports. Under the constrained abstraction policy, even less groundwater becomes available for food production. Increased crop prices are modelled to increase from 39% (sweet potato) from the base climate to 179% (pigeon peas) under the most severe climate scenario.

Table 2 shows that crops with the lowest price elasticity of demand, typically food grains, can expect to see the greatest increases in food price with greater climate-water stress. Food buyers suffer with higher crop prices as these higher prices signal an absolute increase in food scarcity. Farmers can better afford the decline in yield associated with less precipitation and higher crop prices, since higher prices can increase producer surplus (farm income). In that case farmers can be expected to have the financial capacity to invest in new irrigation

Table 2
Average Farm Gate Crop Price by Abstraction Policy and Climate Sscenario, 1000 $ US per ton.

Crops	Unconstrained Groundwater Abstraction				Constrained groundwater abstraction			
	Base Scenario	RCP 2.6	RCP 4.5	RCP 8.5	Base Scenario	RCP 2.6	RCP 4.5	RCP 8.5
Sugarcane	0.11	0.15	0.15	0.17	0.13	0.17	0.17	0.17
Sweet potato	0.49	0.59	0.61	0.67	0.57	0.49	0.59	0.68
Sweet peppers	0.82	0.95	0.98	1.09	0.89	0.97	1.01	1.23
Cassava	0.17	0.24	0.26	0.34	0.28	0.18	0.23	0.37
Tomato	0.82	0.97	1.00	1.15	0.95	0.87	0.99	1.26
Cabbage	0.44	0.53	0.55	0.66	0.56	0.41	0.50	0.70
Cucumber	0.31	0.41	0.44	0.55	0.44	0.32	0.40	0.62
Okra	0.73	0.93	0.98	1.21	0.97	0.73	0.91	1.32
Onion	0.39	0.45	0.47	0.54	0.45	0.37	0.45	0.56
Pigeon Peas	1.06	1.71	1.87	2.64	2.09	1.30	1.72	2.96
Pumpkin	0.23	0.32	0.35	0.45	0.35	0.25	0.32	0.51
Squash	0.42	0.55	0.59	0.75	0.60	0.42	0.53	0.79
Other Crops	0.39	0.45	0.47	0.54	0.45	0.37	0.45	0.56

technology such as drip irrigation.

4.4. Livelihoods

Our results show that climate change can be expected to produce major economic impacts on livelihoods in addition to impacts on water availability and water use, as our optimization model is designed to minimize the economic costs of adapting to growing climate stress as well as minimize adjustment costs to a policy that would protect terminal aquifer storage. Table 3 presents several indicators of overall water sector economic performance, including discounted net present value of producer surplus, consumer surplus, and total economic welfare, by sector, abstraction policy and climate scenario, in $US millions. Consumer surplus is the economic value of food security measured by the cost savings from baseline crop prices compared to maximum willingness to pay. The table shows total economic welfare, the sum of producer surplus and consumer surplus, an indicator of overall water sector economic performance. Overall optimized economic welfare is shown for each of the eight model runs in the lower right corner.

Table 3 also illustrates that food buyers pay for the consequences of the climate change in the long run as well as aquifer protection in the shorter run. Increased food prices reduce the consumer welfare (consumer surplus) from reduced food affordability. Similarly, under a greater climate stressed future, resultant higher food prices will take place and therefore a reduction in consumer surplus occurs. These results have occurred often in historic periods of food shortage (Bouman et al., 2007; Chabot and Dorosh, 2007; Easterling and Apps, 2005; Gregory et al., 2005; MacDonald et al., 2009). Likewise, constraining groundwater abstraction will elevate stress on food security and food consumers, especially poor ones, who shoulder the largest burden of that stress. The table also shows zero loss in urban producer welfare (the local water utility) under unconstrained pumping because higher water prices are assumed to offset higher costs of production, a policy measure currently implemented in Barbados to protect the utility's financial viability.

4.5. Policy implications

Two groundwater abstraction policies for handling each of four levels of climate water futures are presented in this work. All eight model runs come from a separate economic optimization model for which pumping and use are guided by varying sets of constraints. Although not investigated in this work, reductions in groundwater storage could possibly be mitigated by improving the internal water supply, such as the development and use of harvested rainwater augmented by infrastructure such as rooftop rainwater harvesting (not shown). Implementation of a program of subsidized rainwater harvesting would have two effects. First would be an additional and yet unrealized resource which augments existing resources, although at a higher cost. Second, its use could reduce pressure on the existing supply system, though not necessarily reducing demand. The incorporation of rainwater harvesting has been found in some cases can be a low-cost climate adaptation strategy (Domenech and Sauri, 2011) and, depending on rainfall, access and cost of rainwater harvesting, could be economically justified to incorporate its promotion into a mix of water policy elements (Abdulla and Al-Shareef, 2009; Boers and Benasher, 1982; Daigger, 2009; Pandey et al., 2003; Tal, 2006).

A question that has been raised in policy debates is what effect large scale rainwater harvesting would have on existing water use or rights to that use (Chen et al., 2017), such as senior or adjudicated water rights

Table 3
Discounted Net Present Value of Producer Surplus, Consumer Surplus, and Total Welfare, by Sector, Abstraction Policy and Climate Scenario (Million $ US).

Climate/abstraction		Agricultural		Urban		Total	
		Unconstrained	Constrained	Unconstrained	Constrained	Unconstrained	Constrained
Producer Surplus	base	25	40	0	8.6	24	49
	RCP2-6	49	36	0	10.2	49	46
	RCP4-5	51	47	0	10.0	51	57
	RCP8-5	57	54	0	10.1	57	64
Consumer Surplus	base	773	762	22	11.5	795	774
	RCP2-6	754	756	22	7.6	776	764
	RCP4-5	752	751	22	8.1	774	759
	RCP8-5	747	747	22	7.4	769	754
Total Economic Welfare	base	798	802	22	20	819	823
	RCP2-6	803	792	22	18	824	810
	RCP4-5	803	798	22	18	825	816
	RCP8-5	804	801	22	17	826	818

impaired by rainwater harvesting that intercepts flows into rivers and aquifers that would have otherwise permitted economically viable water abstraction (Oweis and Hachum, 2006). Financial incentives needing to be established to encourage widespread uptake to make a significant impact on overall consumption patterns as well as financial impacts on water utilities of the displaced water consumption all need attention. In some cases, the utility could establish its own rainwater harvesting program, though the threat of water rights impairment in some cultures still remains.

Despite the numerous findings of our work, questions of how water sector policies can impact the national groundwater resources availability for SIDS when facing climate change remains an important research inquiry that need investigation by future work. The impacts of trade policies on food security and groundwater resource sustainability based on the notion of virtual water (Aldaya et al., 2010; Allan, 1998; Allan, 2003) in which reduced exports and increased imports of water-intensive goods occur, can provide important insights to guide future research. Another limitation in our current work is the investigation developing a new source of water supply such as desalination technology as well as its impact on groundwater sustainability and food security under the growing threat of climate change for SIDS. All these must be left to future research investigations.

5. Conclusions

Small Island Developing States (SIDS) show high vulnerability to climate change, where they depend mainly on the groundwater system to support food production, demand for urban users, and environmental needs. Despite that increased interest in projecting the impact of climate change, less attention is typically paid to the economic impact of climate change and to economically viable adjustment mechanisms. More important, the impact of climate change on different water users is often investigated piecemeal, and typically in isolation with the potential impact of climate change on water resources availability. So, it is not surprising to see that some adaptation and mitigation policies, while they produce desirable effects at a targeted micro level, can result in high levels of external costs when accounted for at a larger geographic level (Grafton et al., 2018).

The framework established in this work that integrates climate change, hydrology, institutions, economics, and policy design across water related sectors provides a more integrated understanding for the interrelated impact of climate change among competing sectors. The kind of integrated analysis presented here can provide better guidance for adaptation and mitigation policy design and implementation. In this research, an integrated groundwater management framework that maximizes total economic welfare from allocating scarce groundwater among competing sectors, different time periods, and under different climate based driven scenarios is developed. The economic impacts of three Representative Concentration Pathway climate scenarios (RCP2.6, RCP4.5, and RCP8.5) in addition to the base climate condition on the groundwater sustainability for long run was investigated. In addition, impacts of two groundwater abstraction policies on food security and urban water consumer livelihoods was investigated. The framework developed has been applied for Barbados as an example of a SIDS that faces growing challenges meeting demand for urban and food production purposes, with high vulnerability to climate change.

Findings indicate that groundwater sustainability is under threat in the long run with a need for informed management and policy implementation supported by sophisticated modelling such as presented in this work, even with only modest threats imposed by climate change. With no action taken to sustain water use, food consumers in our study region can expect to see higher food prices although there will likely be some offsetting import growth to the extent that Barbados can afford to pay for those increased imports. Future food buyers will pay for weak current groundwater protection policies through higher food prices unless affordable food imports can be secured in through other measures, such as strategic political alliances.

For future work, we hope to investigate the feasibility of achieving food security protection measures that may be currently difficult to achieve in the face of international food price fluctuations over which SIDS typically have little effective control. Relying on imported food when stability of those imported prices are not assured in future years may be a riskier strategy than taking measures to assure sufficient domestic food production in SIDS such as Barbados, as many food importing countries have discovered historically.

Constraining groundwater abstraction will produce negative effects on all sectors' economic welfare in the short run. Still, the negative impact from sustaining the groundwater resources will be less than negativity produced by climate change. For future work, we hope to investigate the potential that the water authority could possibly reduce its net financial loss by operating more efficiently under climate change and by constraining groundwater abstraction, and investigating alternative water sources. That is, the average deficit in water utility's budget could be less with higher climate emission scenarios as less water supplied with attendant reduced financial deficits, especially with a higher tariff charged. By constraining groundwater abstraction, the net financial loss, mainly from household subsector, could turn to a net gain, though not investigated in this work. More adaptation strategies could be investigated not currently covered by this work, as could more constraints for promoting social justice in water use. Improving the water network distribution system by reducing the network loses, reuse of wastewater, and investment in desalination technology could be productive measures. Investigating the feasibility of those alternatives is left for future investigation.

Finally, the scope of our work is limited to one particular SIDS, so some healthy skepticism of our findings is in order, as it is difficult to be completely confident for a small area like Barbados even with access to downscaled climate models. In that light, we conclude this paper by presenting an open challenge to the climate-water-economics-policy research community, who are encouraged to be conservative in model interpretations to inform policy design until their approach can be replicated to more and larger SIDS.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2018.12.008.

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